THERMOACOUSTIC ENGINE-GENERATOR

BACKGROUND OF THE INVENTION

The subject invention originates from twenty-two years research by the inventor, into engines and resonators that operate on the principles of thermoacoustic physics. For purposes of

5   this application for patent, the term "thermoacoustic" refers to traveling energy impulses, normally detected as pressure fluctuations, propagating along velocity vectors that move thermal energy through an elastic medium that is typically a compressible working fluid. For purposes of this application for patent, thermoacoustic energy includes both shockwaves (supersonic and hypersonic pressure waves) and sound waves (pressure waves traveling at the sonic velocity of

10   the working fluid under locally extant conditions).

The research background data in heat, acoustic wave phenomena and gas mechanics includes the shock tube research performed by government and institutional scientists during the 1950's and 1960's, relevant examples of which can be found in the *Proceedings of the Seventh International Shock Tube Symposium*, University of Toronto Press 1970, ISBN 0-8020-1729-0;

15   as well as research into thermoacoustic waves generated by chemical explosives, *The Chemistry of Powder and Explosives*, Volume I, 1941, Volume II, 1943, by Tenney L. Davis, Ph.D., ISBN 0913022-00-4; published research in atmospheric physics, including *Lightning*, by Martin A. Uman, McGraw-Hill 1969; *The Flight of Thunderbolts*, 2nd ed., B.F.J. Schonland, Clarendon Press 1964; *Graphic Survey of Physics*, by Alexander Taffel, Oxford Book Company 1960;

20   *Matter and Motion*, by James Clerk Maxwell, 1877, Dover Publications 1991 (reprint); *Laboratory Exercises in Physics*, Fuller and Brownlee, Allyn and Bacon 1913; *Laboratory Experiments in Elementary Physics*, by Newton Henry Black, Macmillan Company, 1944; *Modern Physics*, by Williams, Metcalfe, Trinklein and Lefler, 1968, Holt, Rinehart and Winston Publishers; *Physics of Lightning*, D.J. Malan, The English Universities Press Ltd., 1963; which

25   includes thermoacoustic phenomena generated by natural lightning and man-made electric arcs.

Other relevant published research includes work in pulse tube refrigeration, including *The Influence of Heat Conduction on Acoustic Streaming*, Nikolaus Rott, Journal of Applied Mathematics and Physics (ZAMP), vol. 25, pp. 417-421, 1974; *A Review of Pulse Tube Refrigeration*, Ray Radebaugh, Cryogenic Engineering Conference, pp. 1-14, 1989; *Flow*

Patterns Intrinsic to the Pulse Tube Refrigerator, J. M. Lee, P. Kittel, K. D. Timmerhaus, R. Radebaugh, National Institute of Standards and Technology, pp. 125-139, 1993.

5   The cryogenics department at NASA-Ames is a premier focus of pulse tube refrigeration research. Pulse tubes differ from most thermoacoustic devices in that they are typically non-resonant devices in which a mechanical piston, driven by an external power source, generates compression waves (pulses) that move in one direction through a series of heat exchangers, and cause thermal energy to be transported between those heat exchangers. Pulse tubes are typically used in cryogenic refrigeration applications. Pulse tubes are similar to most thermoacoustic devices in that traveling pressure waves in an elastic working fluid are the mode of operation.

10   The research history involving prime movers with associated thermoacoustic characteristics includes *Stirling Cycle Machines,* by Graham Walker, PhD, 1973, Oxford University Press; various Stirling engine technical research reports, 1937 – 1978, issued by The Philips Company Laboratories, Eindhoven, Netherlands; and Stirling Cycle Engines, by Andy Ross, 1977, published by Solar Engines, Phoenix, Arizona.

15   The device described herein is a traveling-wave Thermoacoustic Cycle (TAC) engine-generator set, comprised of a gas tight housing containing a compressible working fluid under pressure in which acoustic traveling waves are caused to propagate; a multiplicity of heat exchangers in which said acoustic traveling waves are amplified by a thermal gradient that causes said acoustic traveling waves to increase in pressure and temperature amplitudes and in wave

20   propagation velocity; and an electrodynamic armature that said acoustic traveling waves impinge upon and cause to reciprocate within a magnetic field generating means in order to generate electrical energy.

TAC engines are well known to acoustic science, are in USPTO Class 310 and International Class H01L 041/08, and have been explored extensively by Peter H. Ceperley,

25   George Mason University; Steven Garrett of Penn State University and Gregory Swift of Los Alamos National Laboratory. Thermoacoustic related patents searched include:

6,385,972 May., 2002 Fellows	60/517
6,054,775 Apr., 2000 Vocaturo	290/1R
6,032,464 Mar., 2000 Swift, et al	60/517

	5,953,920 Sep., 1999 Swift, et al	60/520 X
	5,892,293 Apr., 1999 Lucas	90/1R
	5,673,561 Oct., 1997 Moss	62/6
	5,659,173 Aug., 1997 Putterman, et al	250/361
5	5,647,216 Jul., 1997 Garrett	62/6
	5,519,999 May., 1996 Harpole, et al	60/520 X
	5,515,684 May., 1996 Lucas, et al	62/6
	5,456,082 Oct., 1995 Keolian, et al	62/6
	5,319,938 Jun., 1994 Lucas	62/6
10	5,303,555 Apr., 1994 Chrysler, et al	62/6
	5,295,355 Mar., 1994 Zhou, et al	62/6
	5,275,002 Jan., 1994 Inoue, et al	62/6
	5,269,147 Dec., 1993 Ishizaki, et al	62/467
	5,263,341 Nov., 1993 Lucas	62/6
15	5,165,243 Nov., 1992 Bennett	62/6
	4,722,201 Feb., 1988 Hoffler, et al	62/467
	4,686,407 Aug., 1987 Ceperley	60/721
	4,599,551 Jul., 1986 Wheatley, et al	322/2R
	4,398,398 Aug., 1983 Wheatley, et al	62/467
20	4,355,517 Oct., 1982 Ceperley	60/721
	4,114,380 Sep., 1978 Ceperley	60/721

Standing wave Thermoacoustic Cycle (TAC) engines are typically comprised of a gas tight resonant cavity in the approximate shape of a cylinder, tube or torus, and internal isothermal heat exchangers that are separated by a regenerative heat exchanger (stack) and spaced along the

25 length of the resonant cavity by a nominal wavelength or fraction thereof. An applied difference in thermal potential, across the length of the cavity, is created by a thermal gradient between the two isothermal heat exchangers. In standing wave resonators, the thermal gradient alone is sufficient to produce and amplify acoustic waves which transport thermal energy from one heat

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exchanger to another, and to maintain a state of oscillation, or periodic thermal and acoustic flux, in the working fluid.

To extract useful work from the engine, the oscillating pressure component can be applied to a mechanical member, such as a piston, in order to perform reciprocating work, and thereby

5   used to perform tasks such as pumping fluids or generating electrical energy.

TAC engines have been researched for several decades, and researchers at the Los Alamos National Laboratory, the Naval Post Graduate School, The University of Texas, Penn State University and other institutions have written numerous research papers on the genre, primarily concerning standing-wave thermoacoustic physics. A standing-wave thermoacoustic refrigerator

10   developed by Steven Lurie Garrett was flown aboard the space shuttle *Discovery* in 1991 as an experimental package. It is mentioned (project 511) along with this inventor's Acoustic Cycle engine (project 503) in the *1993 Rolex Awards For Enterprise*, published December, 1992. Currently, there are approximately thirty relevant patents in the field.

The most significant problem with prior art thermoacoustic engines and refrigerators is

15   that they have a very low power density. They are typically much larger and more massive for the amount of output work they produce, than other types of engines and refrigerators. Until 1998, disregarding non-resonant pulse tubes, most researchers working in the field, including Gregory Swift's Los Alamos group, concentrated their efforts largely on thermoacoustic engines that employed standing wave physics. The power output of standing wave systems is limited by the

20   inherent physical characteristics, to wit; standing wave systems rely on the forward-going wave being inverted and reflected uniformly back along the resonator at nearly the same propagation velocity. If too much energy is extracted from the forward-going wave in the cold-side heat exchanger, the propagation velocity of the return wave is changed and the forward-going wave and the return wave will be out of phase and will interfere with each other. This adds impedance

25   to the cycle and tends to damp the oscillation. This inherent characteristic severely limits the quantity of energy per cycle that is available to perform useful work, resulting in large engines with low power density.

Traveling-wave engines and pulse tubes, by comparison, do not rely on reflected waves to maintain system oscillation. Traveling-wave engines ideally eliminate the reflected wave, and

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propagate thermoacoustic energy in only one direction, thereby reducing the impeding effects of a change in wave propagation velocity on the system, and increasing the amount of useful energy that can be extracted from the system. All traveling-wave thermoacoustic engines, to some degree, experience a phenomenon known to practitioners of the art as "streaming". The term

5 refers to the physical motion of the working fluid. Where the desirable state of operation in most thermoacoustic engines is such that the mass of the working fluid resides in a static state, with the energy transport confined to pressure impulses (acoustic waves) that transit the working fluid, streaming is considered as an impedance; an undesirable effect. Streaming can be caused by convection currents and by physical displacement of the working fluid mass by the pressure

10 impulses. This is typically problematic only in traveling-wave engines, where the energy impulses travel in only one direction.

In 1998-99, Greg Swift of Los Alamos attempted to improve on prior art by coupling Ceperley's torus-shaped traveling-wave engine with a cylindrical standing-wave resonator, in an effort to produce greater output power from the traveling-wave component, without damping the

15 standing-wave oscillator. He also added mechanical elements to inhibit streaming. Even so, the compound engine develops low energy density because the design still relies mainly on conventional acoustics theory and geometry to produce an engine that is acoustically resonant.

BRIEF SUMMARY OF THE INVENTION

The subject invention described herein is a traveling-wave thermoacoustic engine that

20 conquers the problem of low power density through use of a design methodology conceived and developed by the inventor, in which metered, low velocity streaming is encouraged in order to reduce the size of heat exchangers while still maintaining a desired temperature differential in the working fluid, and the wave propagation velocity and temperature-pressure gradients are increased and amplified by means of a combination heat exchanger-waveguide that has acoustic

25 characteristics similar to an exponential horn.

Thermal energy amplifies the traveling wave in the same manner as is described in United States Patent #6,385,972 May, 2002, Fellows, 60/517. The primary differences between the MEMS Thermoacoustic Resonator that is the subject of the aforementioned patent and the subject of this patent application are in physical geometry and physical size. The combination

waveguide-heat exchanger is designed so as to present the heated area of the waveguide more effectively to heat streams comprised of flowing fluids such as exhaust gases from combustion engines, and heated liquids. Whereas the purpose of the miniature Thermoacoustic Resonator in U.S. Patent 6,385,972 May, 2002, Fellows, is to harvest radiant energy, and thermal energy via

5   conduction through contact with hot surfaces, the subject invention of this application is meant primarily to harvest waste energy from fluid heat streams.

The science of acoustics, like the electrical sciences, is concerned with the transmission of energy through a conductive medium. The type of medium determines its impedance characteristics; its resistance to the energy flow; and to the coupling efficiency, or energy

10   transmission ratio, when one medium interfaces with another. The energy state of the medium, including temperature and pressure, also effects impedance and coupling efficiency when a medium in one energy state interacts with the same medium in a different energy state. These characteristics become particularly evident in Fellows patent #6,385,972, May 14, 2002, in which the thermo-reactive properties of solids and fluids are engineered to increase energy transmission

15   and coupling efficiency in a variety of energy conducting media in order to increase the energy density; and thereby the specific power to weight ratio of thermoacoustic engines.

As in United States Patent #6,385,972 May, 2002, Fellows, the principal improvement on prior art is a significant increase in power density. As described above, the combination acoustic horn waveguide and heat exchanger performs two basic functions. First, the waveguide-heat

20   exchanger HX sub h changes the state of equilibrium in the working fluid that is migrating through it by creating a velocity gradient in the acoustic waves that transit the working fluid, as well as a pressure-temperature gradient. Both gradients increase in the same direction. Second, the geometry of HX sub h is engineered to present less impedance to the acoustic waves traveling in the same direction as the increase in gradients. The waveguide function of HX sub h is similar

25   to that of an exponential or hyperbolic horn. Horns are essentially impedance-matching acoustic transformers; waveguides that are designed to efficiently couple the energy of a medium in a given energy state, with the same medium in a different energy state.

In the subject invention, the tapered, horn-like waveguide offers a progressively greater cross-sectional area to the working fluid, thereby presenting a corresponding decrease in

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impedance to acoustic waves traveling in one direction, and thereby promoting unidirectional acoustic wave propagation. Energy is also progressively added to the working fluid and the acoustic waves via thermal conduction through the walls of the waveguide. The conductive area of the waveguide increases in the direction of increased cross-section which means that the energy

5   conveyed to the working fluid increases progressively in the direction of wave propagation. These factors combined tend to progressively increase the sonic velocity of the working fluid in the direction of wave propagation and to progressively amplify the acoustic energy gradient in the acoustic wave-train.

       In operation, a parcel of the static working fluid is pumped from the cooler section HX

10   sub c into the heated waveguide by an acoustic wave generating means, said acoustic wave generating means preferably being a flexible piston diaphragm arrangement, similar in function to a loudspeaker or a bellows-type air pump, affixed at its center to the free moving generator armature shaft and affixed at its periphery to the inner wall of the generator housing. The acoustic wave generating means, so configured, therefore doubles as a flexible spring suspension

15   and mounting means for the armature shaft, and a pneumatic piston.

       The parcel of working fluid is slightly compressed by the action of the acoustic wave generating means, and expelled through a check valve into the throat of the waveguide. Upon entering the waveguide, the parcel begins to take up heat and to increase in temperature, pressure and propagation velocity. It expands, thereby generating a thermoacoustic wavefront, a traveling

20   wave pressure impulse that expands through the waveguide in the direction of least resistance. As the parcel continues to take up heat, expansion forces and waveguide geometry propel the parcel (thermoacoustic wavefront) toward the mouth of the waveguide. The thermal energy, pressure and sonic velocity gradients of the thermoacoustic wavefront continue to increase in relation to the increase in heated surface area and volume of the horn, as the wavefront transits the horn

25   along the axis of the waveguide HX sub h from throat to mouth.

       The wavefront exits the waveguide into an acoustic wave driven means. The acoustic wave driven means is a second piston diaphragm similar to the acoustic wave generating means, and also doubles as a second flexible suspension mounting means for the armature, disposed within the generator housing and affixed to the armature and generator housing in the same way

as the acoustic wave generating means, to wit: affixed at its center to the opposite end of the generator armature shaft from the acoustic wave generating means, and also affixed at its periphery to the inner wall of the generator housing.

Said acoustic wave driven means transforms the periodic acoustic energy emitted by the waveguide into pulsating mechanical force that causes the armature to reciprocate in relation to the magnetic field generating means, and thereby converts acoustical energy to mechanical energy to electrical energy.

The acoustic wave generating means and acoustic wave driven means operate similarly to an acoustic loudspeaker system known to practitioners of the art as a passive radiator loudspeaker system, wherein the piston diaphragm of a passive loudspeaker is driven by acoustic waves generated by the piston diaphragm of an active loudspeaker. The passive and active loudspeaker elements are in acoustic communication, via a connecting cavity containing a compressible working fluid, said connecting cavity having geometric dimensions that favor a particular acoustic wavelength. At said particular acoustic wavelength, inside the connecting cavity, the active and passive loudspeakers are 360 degrees out of phase. Externally, they operate in synchronous phase with one another, and reinforce the acoustic energy output of the speaker system.

In the TAC Generator, the acoustic wave driven means is attached to the opposite end of the armature from the acoustic wave generating means, so that the armature, acoustic wave generating means and acoustic wave driven means are physically connected and move together as a single unit. The acoustic wave generating means and acoustic wave driven means are also in acoustic communication via a second path, a loop, formed by the working fluid and waveguide geometry.

By these physical and acoustic means, when the armature is caused to move along its axis by an acoustic wave exiting the waveguide and impinging on the acoustic wave driven means, the acoustic wave generating means also moves and generates a second acoustic wave. At the end of the armature stroke, the armature will be caused to rebound toward its original position. The geometry of the waveguide is such that, given specific physical conditions in the working fluid, the second acoustic wave will exit the acoustic wave generating means and transit the waveguide in a specific period of time and arrive at the acoustic wave driven means at the moment when the

armature has reached the limit of its rebound stroke. The second acoustic wave acts on the acoustic wave driven means and moves the armature through another stroke, which causes another acoustic wave to be generated by the acoustic wave generating means. As long as the appropriate working fluid conditions and thermal gradient are maintained, the cyclic process is

5   auto-regenerative and continuous.

At the end of the armature stroke, the over-pressure created by the thermoacoustic wave is expelled from the acoustic wave driven means into the cooling section HX sub c via a metering orifice. The pressure in the acoustic wave driven means becomes less than the pressure in the acoustic wave generating means and the resultant gas spring action causes the armature to

10   rebound toward its original position. The rebounding armature causes the pressure in the acoustic wave generating means to drop, and working fluid is pulled into the acoustic wave generating means from the cooling section HX sub c.

In the vernacular of the art, the waveguide acts as a delay line, and is so designed as to time the arrival of each acoustic wave so that the armature oscillation becomes resonant, and

15   tends to become self sustaining in its oscillation.

As stated above, the design geometry of the horn waveguide heat exchanger HX sub h is such that when the working fluid attains the operating temperature gradient between heat exchangers HX sub h and HX sub c, the TAC Engine-generator attains resonance and the reciprocating action of the armature tends to become self-sustaining. Each oscillation of the

20   armature pumps another parcel of working fluid into the waveguide; each parcel of working fluid absorbs heat and expands through the waveguide and produces another oscillation in the armature.

The linear electric generator is a combination motor-generator. When heat energy is first applied to HX sub h, controls energize an oscillator circuit and coolant pump. The oscillator

25   sends an alternating current through a winding in the generator field generating means. The oscillator circuit and winding, by inductive action well known to electrical engineering science, cause the armature to reciprocate, thereby generating traveling waves in the waveguide-heat exchanger. As the temperature of the waveguide-heat exchanger and the working fluid increases, thermoacoustic energy begins to take over the task of causing the armature to reciprocate,

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inducing a reverse current in the field windings and causing a bucking voltage to develop in the generator output winding. Said bucking voltage exceeds the motor current from the oscillator circuit, causing the oscillator circuit current to decline as the generator output circuit current increases. When the engine reaches operating temperature, and resonance, current from the

5 oscillator circuit is at a minimum value, at or near zero, and generator output current to an external load is at a maximum value.

The horn waveguide HX sub h is separated from the electric generator and the cooler HX sub c by a thermal insulator, also called a thermal break, that divides the TAC Engine-Generator housing into two sections which are distinguished by the difference in the temperature and

10 dynamic pressure gradients of the working fluid contained therein. The thermal break reduces short-circuit thermal conduction between the waveguide-heat exchanger HX sub h section, and the generator and cooler HX sub c section. Its purpose is to minimize thermal losses from the working fluid via the conductive parts of the engine housing, and to limit the path of energy exchange to the working fluid, thereby reducing energy losses in the invention. The thermal break

15 is located between the waveguide-heat exchanger HX sub h and the generator housing. Said generator housing, in conjunction with HX sub h, contains the working fluid under pressure. Said generator housing is preferably comprised of metal, though ceramics and thermoplastics can also be used in some parts of it. HX sub h is preferably comprised of heat conducting material, typically a metal.

20 The frequency of the generator output current is determined by the engineered properties of all the heat exchangers, and by the geometry of the acoustic waveguide-heat exchanger HX sub h.

The propagation velocity of traveling waves is determined by the nature and operating conditions of the working fluid. In the thermoacoustic engine generator, traveling waves

25 propagate through the working fluid from HX sub h, to HX sub c, transporting thermal energy between the two. Said traveling waves take up energy from an external heat source during transit of the horn waveguide-heat exchanger HX sub h. Said energy causes said traveling waves to increase in sonic propagation velocity, and in pressure and temperature amplitude in accordance with Charles Law. The amplified traveling waves appear to the acoustic wave driven means as a

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periodic fluctuation in the pressure of the working fluid. The oscillation in pressure in the working fluid causes the armature to reciprocate within a magnetic field, and generates an electric current in an electrical field winding. Said electrical field winding is connected to electrical conductors that exit the TAC Engine-Generator housing in the form of terminals that convey the

5   electrical energy from within the TAC Engine-Generator to an external load.

The TAC Engine-Generator can be designed to operate across a wide temperature range. The operating range with common materials is from <100 Kelvins to >1200 Kelvins. Higher temperatures, and thus a wider absolute range, are possible with development of waveguide-heat exchangers comprised of advanced materials, such as ceramics and high-temperature metal alloys.

10   The nominal operating temperature of any individual TAC engine-generator is a relatively narrow range of temperature within that broad range of material capability, at which the device is resonant, and is engineered into the device during manufacture, to suit a specific application and set of operating conditions.

Energy conversion efficiencies are directly related to the temperature gradient across the

15   TAC Engine-Generator. For example, with a cold sink HX sub c temperature of 273K and waveguide-heat exchanger HX sub h temperature of 1210K, theoretical (Carnot) efficiency is 77% (1210K- 273K / 1210K = 0.77), and actual realizable efficiency is 48% (0.77 * 0.63 = 0.48).

Such efficiencies are possible within the nominal limits of commercially available and economical materials, and common fabrication processes such as stamped and machined steel and

20   aluminum components. TAC Engine-Generators may be manufactured in a variety of sizes.

A variety of working fluids are employed in the manufacture of TAC engines. Each working fluid has unique physical properties. Mixtures of the noble gases are the working fluids preferred for the TAC Engine-Generator, though other gases, including air, can also be used. Traveling wave thermoacoustic engines designed for power generation have different working

25   fluid requirements than standing wave thermoacoustic engines used mostly for refrigeration. When refrigeration is the objective, working fluids with high thermal conductivity and specific heats are paramount for efficiency. In traveling wave machines used in mechanical conversion applications such as linear generators, working fluids with high molecular weight are preferred for higher efficiency. The reason for this is that the main energy metric in a traveling wave engine

generator is the kinetic energy delivered to the piston of the linear generator. The formula describing kinetic energy is:

$$W_k = \tfrac{1}{2}\, mv^2$$

For example, the kinetic energy of a traveling wave propagating through air, compared to

5   that of a traveling wave propagating through argon, under a given set of operating conditions, is shown in the table below:

Working Fluid	Mole Wt.	Heat Ratio	Temp. (F°)	Sonic Velocity (ft/sec)	Waveguide Frequency (Hz)	Wt@ 10atm. (lb/ft3)	Thermal Energy Btu/ ft^3	Kinetic Energy lb-ft/sec	Power (hp)
Air	8.96	1.4	900	1807	60	0.74	159	37549	68
Argon	9.94	1.67	900	1681	60	1.02	114	44769	81
Helium	4.00	1.66	900	5297	60	0.1	111	43572	79
Krypton	83.8	1.68	900	1164	60	2.14	113	45044	82
Neon	20.17	1.64	900	2344	60	0.515	114	43945	80
Nitrogen	28.01	1.4	900	1838	60	0.715	160	37517	68
Xenon	131.3	1.67	900	927	60	3.36	347	44869	82

Table 1

The volumetric mass of a confined working fluid does not change from what it is at initial static pressure, however, the pressure per unit of volumetric mass changes directly with the

10   change in absolute temperature (pressure increases by 1/273rd for each Kelvin degree increase), while wave propagation velocity changes as a coefficient of the absolute temperature (the coefficient is 1.414, the hypotenuse of a 90° angle). Therefore, it is desirable to mix gases of different molecular weights and thermal properties in order to obtain working fluids with properties tailored to a specific model of engine generator.

15   As Table 1 illustrates, for a given quantity of heat injected into the thermoacoustic engine generator, the most thermally efficient working fluids are krypton @ 1.38 Btu/hp; argon @ 1.41 Btu/hp, neon @ 1.42 Btu/hp and helium @1.41 Btu/hp. Because of its high sonic velocity, helium is best for small machines with shorter waveguides. Argon has twice the specific heat and thermal conductivity of krypton, which means less initial work for the oscillator, while helium has ten

20   times the specific heat and thermal conductivity of either. The drawback with helium is that it

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requires ten times the static pressure to have a mass-volume ratio equal to argon. Mixing the two gases enhances both the thermal and mass-volume ratios of the resulting compound working fluid. The mixture for a traveling wave thermoacoustic generator will have a larger fraction of the heavier gas, for its kinetic properties, as compared to a standing wave thermoacoustic refrigerator

5 in which the mixture will have a larger fraction of helium, for its thermal properties.

In the thermoacoustic engine-generator, the thermal energy in the traveling waves is rejected to the environment via the cooler HX sub c, after it has done its work. This allows down-stream economizers, which are not part of this invention, to extract additional energy from the heat stream.

10 BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIGURE 1 is cutaway view of the TAC Engine-Generator showing all the component parts.

FIGURE 2 is a cross-sectional view of the armature shaft, field windings, pole pieces and the spring diaphragm pistons that support the armature, showing their relationships when

15 mounted in the generator housing.

FIGURE 3 is a planar view of a typical spring diaphragm piston.

FIGURE 4 is a planar view of the field winding, the output winding, and their related pole pieces.

FIGURE 5 is a side view of the field and output windings, showing the relative plane of

20 their associated pole pieces when mounted in the generator housing not shown.

DETAILED DESCRIPTION OF THE INVENTION

The TAC Engine-Generator will be described with reference to drawings that are not to scale. In the drawing figures, the reference character 2 indicates the component referred to as HX sub h in the specification, and the reference character 7 indicates the component referred to as HX

25 sub c in the specification.

With respect to FIGURE 1; the thermal break 4 is a thermal insulating means, preferably a material such as pressed fiber, ceramic or plastic, although other materials can be used, even metals that are poor conductors of heat. The purpose of the thermal break 4 is to minimize short-circuit thermal conduction between the first heat exchanger-waveguide 2, and the generator

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housing 1 in order to reduce conductive losses and increase thermal-to-electric conversion

efficiency. Maximum efficiency depends upon maintaining the widest possible thermal gradient

between the first heat exchanger-waveguide 2 and the second heat exchanger means 7. The first

heat exchanger-waveguide 2 transfers thermal energy from the external thermal energy source to

5   the internal working fluid, thereby increasing (amplifying) the pressure and temperature gradients

of acoustic traveling waves transiting the first heat exchanger-waveguide 2. The thermal break 4

and the base plate 14 have ports that permit passage of the working fluid, and permit acoustic

wave communication, between the first heat exchanger-waveguide 2 and the acoustic driven

means spring diaphragm piston 8. The amplified acoustic traveling wave exits the first heat

10   exchanger-waveguide 2, passes through the ports in the thermal break 4 and the base plate 14,

causes a periodic pressure excursion within the generator housing 1 cavity where the acoustic

driven means spring diaphragm piston 8 is housed, and acts upon the acoustic driven means spring

diaphragm piston 8, thereby causing the attached armature to move a few millimeters along the

plane of the armature axis toward the second heat exchanger means 7. The armature 10 is

15   comprised of a hollow shaft and shorting rings15. The armature shorting rings 15 are affixed to

the armature shaft 10 and disposed on a plane perpendicular to the armature shaft 10. The

armature 10 reciprocates along the armature shaft axis, thereby causing the shorting rings 15 to

cut the magnetic lines of force created by the generator field windings 6 which surround the

armature 10, and cause an induced electric current to flow in an output current winding not

20   shown. Electromagnetic induction coupling, transformer action and transmission of alternating

current electrical energy are well known in electrical engineering practice. The electric current is

conveyed to an external load by output winding conductors not shown.

As the armature 10 reaches the extent of its travel toward the second heat exchanger

means 7 it completes a half-cycle, and a metering means 13 permits the working fluid to flow

25   through a port in the generator housing 1 at a metered rate, and into the second heat exchanger

means 7, thereby relaxing the pressure gradient caused by the periodic acoustic traveling wave

acting upon the acoustic driven means spring diaphragm piston 8.

The periodic pressure gradient of the acoustic traveling wave exits the first heat

exchanger-waveguide means 2 and acts on acoustic driven means spring diaphragm piston 8,

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moving the armature shaft 10 along its axis and causing the shorting rings 15 to cut the magnetic lines of force generated by field winding 6. This action induces a current to flow in the shorting rings 15 creating a moving electrical field which further induces a current flow in the output winding 16 not shown. The acoustic pressure gradient acting on acoustic driven means spring

5   diaphragm piston 8 is caused to relax by the working fluid metering means 13, and the armature spring mounting means 8 and 12 act to return the armature 10 to its original position, causing the armature shorting rings 15 to again cut the magnetic lines of force generated by the generator field windings 6, in the opposite direction, and inducing a current of opposite polarity in the output winding not shown, thereby completing the cycle. By this linear reciprocating action of

10   the armature 10, alternating current is generated in the output winding.

        The working fluid metering means 13 permits the over-pressure generated in the periodic acoustic traveling waves by the thermal energy flux in the first heat exchanger-waveguide means 2 to bleed through the wall of the generator housing 1 into the pressure vessel 3, and transfer the thermal energy to the second heat exchanger means 7.

15   To further clarify the operation of the engine; during each half-cycle stroke of the armature 10, a parcel of the cooled working fluid is pulled into the generator valve body 9 from the second heat exchanger means 7 through a first check valve means 5. Each alternate half-cycle stroke of the armature 10 causes said parcel of working fluid to be expelled from the generator valve body 9, through a second check valve means 11 disposed within a central opening in the

20   armature shaft 10. By these means, a parcel of cooler working fluid is periodically pumped from the second heat exchanger means 7, passing through the armature shaft 10 and into the first heat exchanger-waveguide means 2 by the reciprocating action of the armature 10.

        When the cooler parcel of working fluid enters the first heat exchanger-waveguide means 2 and mixes with the hotter working fluid contained therein, the parcel rapidly acquires thermal

25   energy and expands in volume in accordance with Charles Law. The physical volume of the first heat exchanger-waveguide means 2 is fixed, therefore the sudden expansion of the newly introduced parcel of working fluid causes a pressure gradient to develop rapidly between the throat and mouth of the first heat exchanger-waveguide means 2. Entropic forces act to equalize the pressure across the first heat exchanger-waveguide means by generating a traveling acoustic

pressure wave moving at the sonic velocity of the static working fluid. The energy of this traveling acoustic pressure wave transits the length of the first heat exchanger-waveguide means 2, passes through the thermal break 4 and enters the cavity in the generator housing 1 where the acoustic driven means spring diaphragm piston 8 is housed. The traveling acoustic pressure wave

5 stalls therein, creating a momentary periodic pressure excursion. The momentary pressure excursion acts on the acoustic driven means spring diaphragm piston 8, causing the armature 10 to reciprocate, then the pressure bleeds off at a predetermined rate and exits via metering means 13 into the second heat exchanger means 7. The thermal energy transported by the traveling acoustic pressure wave is rejected to the second heat exchanger means 7 and a coolant coil, not

10 shown, located therein.

When the working fluid and the heat exchangers 2 and 7 reach their respective optimum operating temperatures, the conditions are such that the traveling acoustic pressure waves develop a periodic thermoacoustic cycle equal in duration to the period of mechanical reciprocation of the armature 10, and the thermoacoustic engine and generator become a resonant system. Each

15 reciprocating movement of the armature 10, caused by each traveling acoustic pressure wave, pumps another parcel of cooler working fluid into the relatively hotter first heat exchanger-waveguide means 2, thereby generating a traveling thermoacoustic pressure wave, and the cycle becomes self-regenerating and repeats for as long as a thermal energy gradient exists between the first heat exchanger-waveguide means 2 and the second heat exchanger means 7.

20 An external oscillator circuit not shown acts to start the thermoacoustic engine-generator by sending an alternating current through a section of the generator output winding 16. The oscillator current induces an alternating magnetic field in the generator output windings 16, said alternating magnetic field acts upon the armature 10 and causes said armature 10 to reciprocate and generate traveling acoustic pressure waves. The current generated by the armature 10 bucks

25 the current from the oscillator. When the thermoacoustic engine-generator is operating in a condition of resonance, oscillator current is at a minimum and output current to the external load is at maximum.

The working fluid is typically under multiple atmospheres of pressure, and is contained by the pressure vessel 3 that surrounds the generator housing 1.

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With respect to FIGURE 2, the acoustic driven means spring diaphragm piston 8 and acoustical traveling wave generating means 12 are supported in a fixed position on their outer periphery by the generator housing not shown, and in turn support the armature shaft 10 at its center and permit limited reciprocating movement of said armature shaft 10 along its axis plane.

5   Said acoustic driven means spring diaphragm piston 8 and acoustical traveling wave generating means 12 cause the armature shaft 10 to remain centered with respect to its axis so that the armature shorting rings 15 can reciprocate in close proximity to the pole pieces of the field windings 6 without coming in contact. The magnetic field generated by the field windings 6 induce electromagnetic and electrical fields in the reciprocating shorting rings 15, which in turn

10   induce a current flow in the electrical output winding 16 not shown.

FIGURE 3 is a planar view of the acoustic driven means spring diaphragm piston 8 and duplicate acoustical traveling wave generating means 12 which also support the armature.

FIGURE 4 is a planar view of the field winding 6, and the output winding 16 showing how their respective pole pieces form a circular stator inside which the armature reciprocates.

15   FIGURE 5 is a side view of the field winding 6 and the output winding 16 showing how their respective pole pieces share the same plane when mounted in the generator housing not shown.

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